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Nonlinear Effects in Low Frequency Inductive Plasmas

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1. Introduction

Modern inductively coupled plasma (ICP) sources tend to operate at low frequencies (several MHz and less) that reduces capacitive coupling and transmission line effects and leads to simpler and lower cost rf power sources and matching circuits. Together with a low neutral gas pressure (1-10 mTorr) this creates a unique combination of conditions where two features of inductively coupled plasmas become most prominent: anomalous (non-collisional) heating and nonlinearity due to the Lorentz force. When the electrons are weakly collisional, the collisionless wave particle interaction (Landau damping) replaces real collisions and becomes the main mechanism of the wave absorption and plasma heating [1]. In this regime, the electron mean free path exceeds the characteristic plasma length scale so that electrons "sample" the electric field over large distance resulting in the electric current being not a local function of the electric field. This regime is often referred to as nonlocal regime as opposite to the local, or short mean free path, highly collisional regime of the classical skin effect. The related property of the low frequency ICP is due to the fact that the nonlinear Lorentz force can be much larger than the force of the inductive electric field [regime of the electron Hall magnetohydrodynamics (EMHD)]. Nonlinear forces in ICP may significantly affect plasma density profile [2], generate higher harmonics of the electric current [3], electrostatic potential [4,5], and modify the skin-effect [6]. In this paper we review the experimental data and theoretical models describing these effects.

Experiments have been carried out in a cylindrical low pressure argon ICP, with a metallic chamber with diameter $2R = 20$ cm and length $L = 10.5$ cm, and a quartz window separating a planar coil from plasma [7]. To enhance nonlinear processes the driving frequency and gas pressure were reduced, correspondingly, to 0.45 MHz and 1 mTorr. The rf discharge was maintained at a discharge power $P = 200$ W. The basic plasma parameters: n_e , T_e , the rf and dc plasma potential have been measured with a Langmuir probe moved along the axial (z) direction. Nonlinear harmonics of the electrostatic potential were directly obtained from Langmuir probe measurements. The ponderomotive potential was calculated as the difference between the dc potential and plasma density. Measurements were made on the discharge axis ($r = 0$) and at a fixed radial position $r = 4$ cm, which corresponds to the maxima of the radial distribution of the azimuthal rf electric field and the radial magnetic field. The electromagnetic fields and the plasma

current density distributions were inferred from magnetic probe measurement made along the axial direction at $r = 4$ cm and along the radial direction at $z = 3.2$ cm. Langmuir and magnetic probe measurement were made over a wide frequency range (0.45 - 13.56 MHz) but here we mainly consider data for $f = 0.45$ MHz where nonlinear effects are largest.

2. Nonlinear plasma polarization in the ICP

Nonlinear polarization potential has not been observed earlier in experiments with inductive discharges. One of the reasons for this was that for a typical ICP driven at 13.56 MHz nonlinear effects are negligibly small. They are significantly increased for lower frequency. Polarization potential is created due to the potential component of the nonlinear Lorentz force [5], while the solenoidal component of the Lorentz force is responsible for the nonlinear harmonics in the electric current [3,5].

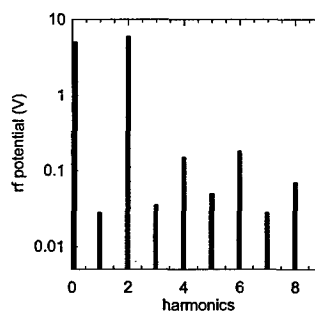


Fig. 1 The frequency spectrum of the polarization potential in the middle of the skin layer, at a distance of 1 cm from the quartz window ($z = 1$ cm, $r = 4$ cm) in an ICP driven at 0.45 MHz.

Note that dc plasma potential (zero frequency, $\omega = 0$) has been deduced from the plasma density and plasma potential profiles while the oscillating rf harmonics have been measured directly. The dc potential corresponds to the nonlinear ponderomotive force. As it is seen in Fig. 1, the first (fundamental) harmonic, induced by parasitic (capacitive) coupling from the induction coil, is smallest, while the second harmonic exceeds the electron temperature and dominates all others. Amplitudes of the second harmonic and dc (ponderomotive) potential are approximately equal for small dissipation.

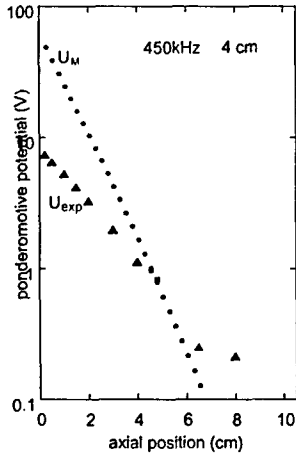


Fig. 2 The experimental value of the ponderomotive potential U_{exp} shown together with the Miller potential U_m .

As shown in Fig. 2 the experimental value of the ponderomotive potential is significantly different from the classical expression for the cold plasma (Miller potential). We have derived an expression for the ponderomotive force in hot plasmas (the strongly nonlocal regime) [8]. This expression can be cast in a form similar to that of the local case, i.e. $F_p = \omega_{pe}^2 / 8\omega\pi E_0^2 \delta_{th}$, where the characteristic gradient length of the electric field δ is replaced with the characteristic length of the particle excursion over the wave period, $\delta_{th} = v_{th}/\omega$.

$$F_p = \frac{\omega_{pe}^2}{8\pi\omega} E_0^2 \frac{\sqrt{\pi}\omega}{v_{th}}$$

This expression is in reasonable agreement with the experimental data [8].

3. Plasma heating at low frequencies

Typically, in the low pressure ICP operating in the anomalous regime, the power absorption due to the interaction with thermal electrons significantly exceeds the collisional absorption. There is an optimal frequency when the power absorption reaches the maximal value. It has been shown that for low driving frequencies and low collisionality $\nu < \omega$ the effects of the particle thermal motion reduce the absorption below the collisional value so that the total electron heating due to both collisional and collisionless mechanisms of wave energy dissipation becomes smaller than it would have been if only the collisional mechanism was involved. This linear effect is illustrated in Fig. 3. Nonlinear effects that are most important for low frequencies may further affect plasma heating [3]. Nonlinear effects have been investigated via direct numerical simulations. In Fig. 2 the ratio of total S_{tot} to the collisional S_{coll}

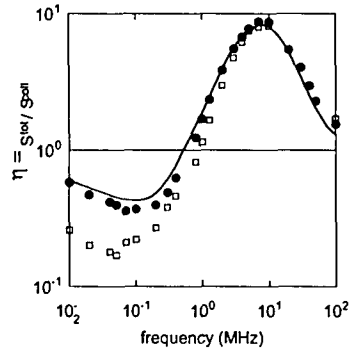


Fig. 3: Ratio of the total to collisional absorbed power. Solid curve represents the linear theory (without rf magnetic field), circles -- the result of PIC simulation without rf magnetic field, squares -- the PIC simulation with rf magnetic field. The parameters are: $E=0.5$ V/cm, $T=10$ eV, $n=2.7 \times 10^{10}$ cm $^{-3}$, $\nu=1.5 \times 10^6$ s $^{-1}$.

heating, $\eta = S_{tot} / S_{coll}$, is shown as a measure of the influence of the electron thermal motion on the electron heating. In numerical calculations the measured absorbed power is averaged over the rf field period. The simulations included electron-atom collisions (implemented into the PIC code with a direct Monte-Carlo method) and the electron-electron collisions (implemented via the Langevin equation) as a mechanism for the "maxwellization" of the electron distribution function. At low frequency there is significant reduction of plasma heating due to the rf magnetic field as a result of expulsion of electrons from the skin layer by the ponderomotive force leads as well as a result of nonlinear trapping of electrons in the rf magnetic field [3].

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References

- [1] M. Lieberman and V.A. Godyak, IEEE Trans. Plasma Sci. **26**, 955 (1998).
- [2] R. H. Cohen and T. D. Roglnien, Plasma Sources Sci. Technol. **5**, 442 (1996); Phys. Plasmas **3**, 1839 (1996).
- [3] V.A. Godyak, R.B. Piejak, B.M. Alexandrovich, Phys. Rev. Lett. **83**, 1610 (1999).
- [4] V.A. Godyak, R.B. Piejak, B.M. Alexandrovich and A.I. Smolyakov, Plasma Sources: Sci. Technol. **9**, 541 (2000).
- [5] A.I. Smolyakov, V. Godyak and A. Duffy, Phys. Plasmas **7**, 4755 (2000).
- [6] J.D. Evans and F.F. Chen, Phys. Rev. Lett. **86**, 5502 (2001); F. F. Chen, Phys. Plasmas **8**, 3008 (2001).
- [7] V.A. Godyak, R.B. Piejak, B.M. Alexandrovich, J. Applied Phys. **85**, 703 (1999).
- [8] A. Smolyakov, V. Godyak, and Y. Tyshetskiy, Phys. Plasmas **8**, 3857 (2001).